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INVESTIGATIONS ON THE PURIFICATION OF BOSTON SEWAGE.*

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I. PURIFICATION OF BOSTON SEWAGE ON TRICKLING FILTERS (1907–9).

1. *Description of experiments.*—Earlier investigations carried out at the Sewage Experiment Station of the Massachusetts Institute of Technology (Winslow and Phelps, 1906; Winslow and Phelps, 1907) have led to the conclusion that sewage of the character of Boston sewage could be purified most satisfactorily and economically by treatment on trickling beds without further preliminary treatment than that afforded by screens and grit chambers. The beds used in the previous work were 8 feet in depth and the filling material was 1½–2-inch broken stone. The studies now reported were mainly directed toward the solution of the question of the best depth for trickling beds to treat Boston sewage and the best size of filling material to use in their construction.

The experimental filters were situated at the Albany Street Experiment Station and the applied sewage was drawn from the

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9-foot trunk sewer of the Boston Main Drainage Works at a point where there is a flow of some 50 million gallons a day from a contributing population of 250,000 (Winslow and Phelps, 1906). It was raised by a 4×6 Warren duplex pump, and roughly settled by passage through a grit chamber, 19 inches in diameter and 16 inches deep, fitted with a screen having bars ½ inch apart, to a small tank on the ground floor. The sewage was then lifted without further sedimentation by a ¾-inch centrifugal pump to a distributing tank in the upper story of the tank house. This distributing tank was 6×4 feet in plan and 3 feet deep, and a constant head was maintained in it by wasting over a 36-inch weir at one end. From the opposite end of the tank, sewage flowed to the trickling filters through two brass orifices whose vertical positions were adjustable. No sludge was removed from this tank, any sludge which temporarily settled out being stirred up and allowed to pass to the filters. The liquid applied to the beds was therefore crude sewage except for the action of the small detritus tank described above and except for the comminution which always attends the passage of sewage through small pipes and pumps.

The filters themselves were outside the tank house in the open air. The total surface was 200 square feet, divided into four units, each 5×10 feet. For a foundation 4×4 spruce sills were buried in the ground and upon them a 1-inch hemlock floor was laid and covered with Portland cement mortar. Half-inch radiating channels in the concrete directed the flow of the effluent to 1½-inch outlet pipes. The sides of the filters were of spruce planks with ½–2-inch openings between them, supported by 4×4-inch studs braced on all sides and tied at the tops by ½-inch iron rods.

The first of the four filter units (A) was filled to a depth of 7 feet with 1–1½-inch broken stone resting on about 1 foot of 3–12-inch boulders. The second (B) was of the same construction except that the stone was coarser, 1½–2 inches in diameter. This stone was the same that had been used for two years in the previous experiments (Winslow and Phelps, 1907). The third filter (C) was just like B in construction, but only 5 feet deep instead of 8. Filter D was at first constructed like C except that the surface foot was of finer material, ½-inch stone. This fine filter clogged so badly, how-

ever, that after four months' use it was dug out and replaced by a bed built of brick somewhat after the fashion of a Dibdin slate bed. Ordinary building bricks, approximately $2 \times 4 \times 8$ inches, were laid so as to overlap as little as possible on the corners, forming a bed with nearly half its total capacity as open space.

The effluent from the four filter units passed by $1\frac{1}{2}$-inch pipes into the tank house and there the effluents from A and B and from C and D were mixed and sedimented in two secondary sedimentation tanks for the removal of suspended solids. Each tank was a simple inverted cone with a diameter of 7 feet 2 inches at the top and a depth of 4 feet. At the center of each tank a vertical funnel 6 inches in diameter extended to within 15 inches of the bottom. The filter effluents were discharged into the top of this funnel and passed out into the tank through lateral openings near the bottom. They ascended with decreasing velocity and overflowed at four points through skimming-troughs at the surface. The storage period in the tanks was about 2 hours.

Sewage was applied to Filters A and B from a single gravity distributor of the type devised at the experiment station and described in earlier publications (Winslow and Phelps, 1907). The sewage was conducted to the center of the double bed in a 3-inch wooden trough from which it dropped through a $\frac{3}{4}$-inch opening in the bottom of the trough on to a concave disc from which it splashed upward and outward. The splash cup was 3 inches in diameter and its concavity had a 6-inch radius. It was supported 1 foot above the surface of the bed and 3 feet below the bottom of the trough. Filters C and D were dosed from below with a Columbus sprinkler nozzle having a $\frac{9}{16}$-inch orifice and a 90° cone above for spreading the spray. This nozzle was dosed intermittently from a siphon tank under a head varying between 4 feet and 3 feet and taking $1\frac{1}{2}$ minutes to discharge and 2 minutes to fill.

Samples of sewage and effluents were collected day and night at intervals of three hours, chloroformed, mixed, and analyzed at the end of the week. Chemical determinations were made by the standard methods of the American Public Health Association, modified in respect to nitrate and free ammonia as discussed in our previous paper (Winslow and Phelps, 1907). Daily samples of all

effluents were tested for stability by the methylene blue test and the results are expressed in terms of "relative stability" as defined in an earlier paper (Phelps, 1909).

2. *General results of trickling filtration.*—All four filter units were operated during the course of the experiments, October, 1907, to May, 1909, at a rate of about 1,500,000 gallons per acre per day. The actual net figures as determined by ratings of the mixed effluents from each pair were 1,280,000 gallons per acre per day for Filters A and B and 1,320,000 gallons per acre per day for Filters C and D.

In regard to the practical working of the beds there were important differences corresponding to the size of the filling material. While Filter D was operated on the first plan, with a 1-foot layer of half-inch material on the surface, it clogged badly. It is clear that half-inch material cannot be used for the treatment of crude sewage like that at Boston. A (1–1½-inch stone) and B and C (1½–2-inch stone) all clogged somewhat during the first winter, but the clogging of A was the most serious. On four occasions it was necessary to rake up a few inches of stone from Filter A to the corners of the bed, and the same thing was done to B twice. The surface of Filter C on the other hand required no attention. It was evident that the more perfect dosing from the Columbus nozzle was a distinct advantage. After the first winter all the beds cleared up considerably and no material was actually removed from any of them. The surface of Filter A remained more or less clogged, however, and it was evident that filtering material under 1½ inches would not operate successfully with crude Boston sewage.

Since the experiments began in the autumn, there was a long period of ripening before the filters were really doing effective work. The quarterly averages in Table 1 show that none of the effluents had a relative stability over 35 for the first six months of operation. With the warm weather of spring all but Effluent D began to improve, reaching a stability of 50–70, and in the autumn quarter Effluents A and B attained a stability over 80. When the filters were once well ripened good conditions were maintained through the winter and spring of 1909. The free ammonia values show the same relation. For Effluent A the free ammonia averaged 13.4 for

the first three quarters and 6.8 for the last four. For Effluent B the figures were, respectively, 13.0 and 7.9. Nitrites appeared in considerable amounts only in the spring and summer of 1908; and after the nitrite-forming bacteria had established themselves the nitrate-formers began their work. The whole cycle of ripening exactly paralleled that recorded in the experiments of the previous two-year periods (Winslow and Phelps, 1907).

The average results for the sewage, the four trickling effluents and the two sedimentation effluents for the last year of operation, are brought together in Table 2. Quarterly averages for the whole 20 months are given in Table 1; but a fairer idea of the actual working of the process may be gained by excluding the preliminary period of ripening.

It appears from the table that all the filters effected an appreciable though not a large reduction in suspended solids. Whatever reduction did occur may probably be accounted for by storage in the beds, as other experiments have shown that trickling beds do not effect a marked diminution of suspended matter. A distinct change from volatile to fixed solids is evident, however, every effluent showing a considerable reduction in volatile suspended matter and an increase in fixed suspended solids. Organic nitrogen is only slightly reduced as compared with the sewage value but free ammonia shows a reduction of 24 per cent for Filter D, 37 per cent for Filter C, 46 per cent for Filter B, and 54 per cent for Filter A. Nitrites in all the effluents average from 0.5 to 0.8 parts and nitrates from 4.2 for Filter D to 6.6 for Filter B. Oxygen consumed values show for the two best filters, A and B, a reduction of 32 per cent in the total oxygen consumed and 34 per cent in soluble oxygen consumed; as determined in fifteen minutes in the cold, the reduction was about the same for the total oxygen consumed (31 per cent), but distinctly better for the soluble portion (40 per cent). Oxygenation was fairly satisfactory in all the effluents, the average value of 2.2 parts for the crude sewage being increased to from 5.6 to 8.1 parts.

The analytical data show comparatively slight differences, aside from the tests for organic stability. Effluent D has a considerably larger proportion of suspended solids, as would of course be expected from its coarse construction. There are two significant

TABLE I.

ANALYSES OF SEWAGE AND EFFLUENTS, 1907–9. QUARTERLY AVERAGES.

Average of Months	Parts per Million															Relative Stability	Temp. Fahr.
	Turbidity	Sediment	Suspended Solids			Nitrogen as						Oxygen Consumed				Dissolved Oxygen		
			Total	Vol.	Fixed	Total	Organic Total	Organic Sol.	Free NH_3	N_2O_3	N_2O_5	30′ Boiling Total	30′ Boiling Sol.	15′ Cold Total	15′ Cold Sol.			
CRUDE SEWAGE.																		
Oct., Nov., Dec., 1907...	246	106	149	85	64	27.0	6.5	2.5	18.0	0.0	0.0	65	47	11.6	7.6	4.0	..	53
Jan., Feb., Mar., 1908...	203	57	212	152	60	31.7	10.6	3.5	17.6	0.0	0.0	74	48	11.8	7.5	6.1	..	44
Apr., May, June, 1908...	204	55	171	126	45	38.4	12.7	7.3	18.4	0.0	0.0	68	54	14.1	10.3	1.6	..	59
July, Aug., Sept., 1908...	183	68	147	98	49	28.8	8.7	4.3	13.8	0.0	0.0	50	42	12.4	8.0	0.0	..	71
Oct., Nov., Dec., 1908...	262	109	147	98	49	29.9	9.5	5.1	15.2	0.0	0.1	57	41	11.4	8.1	3.1	..	55
Jan., Feb., Mar., 1909...	300	156	142	112	30	35.3	11.7	9.8	12.6	0.2	1.0	53	26	10.3	6.8	3.8	..	43
Apr., May, 1909.........	317	125	98	96	2	34.7	9.2	7.1	17.1	0.1	1.2	69	43	13.2	9.3	2.1	..	51
EFFLUENT A.																		
Oct., Nov., Dec., 1907...	146	50	65	62	3	23.6	4.9	2.6	14.6	0.0	1.5	39	34	6.3	5.4	7.9	30	45
Jan., Feb., Mar., 1908...	146	47	128	92	36	27.9	7.3	2.7	15.4	0.2	2.3	49	37	8.4	6.6	9.2	30	36
Apr., May, June, 1908...	200	118	299	169	130	34.1	11.8	5.5	10.3	0.7	5.8	57	37	14.2	6.5	8.0	68	55
July, Aug., Sept., 1908...	94	53	95	57	38	21.3	6.4	4.3	5.9	0.7	4.0	36	29	7.3	5.5	7.4	88	68
Oct., Nov., Dec., 1908...	105	68	93	58	35	25.4	6.8	3.4	4.9	0.6	6.7	32	23	5.9	3.5	8.5	95	48
Jan., Feb., Mar., 1909...	129	89	96	72	24	27.4	7.1	4.1	7.7	0.3	8.2	25	16	6.6	4.0	8.7	80	39
Apr., May, 1909.........	293	246	161	114	47	37.2	15.6	8.4	8.8	0.4	4.0	62	32	13.1	6.5	7.7	81	48
EFFLUENT B.																		
Oct., Nov., Dec., 1907....	138	48	116	57	59	25.2	5.6	4.2	12.2	0.2	3.0	40	33	7.1	5.3	7.8	32	46
Jan., Feb., Mar., 1908...	125	38	177	137	40	27.6	6.0	3.1	13.9	0.1	4.5	42	32	7.2	5.5	9.4	30	36
Apr., May, June, 1908...	201	124	315	198	117	35.5	11.0	5.4	13.0	0.6	5.5	63	39	14.6	7.2	7.7	63	54
July, Aug., Sept., 1908...	113	72	89	58	31	22.4	6.0	4.1	8.1	0.8	3.4	39	32	8.5	6.2	6.9	81	69
Oct., Nov., Dec., 1908...	123	87	97	66	31	25.1	7.5	2.9	7.3	0.8	6.6	35	25	6.7	3.9	7.3	87	49
Jan., Feb., Mar., 1909...	155	111	100	66	34	27.0	6.7	4.3	6.7	0.5	8.8	29	14	6.6	3.5	8.2	92	41
Apr., May, 1909.........	276	240	140	62	78	34.6	11.2	6.2	9.4	0.3	7.5	52	28	10.6	5.5	7.1	91	50

EFFLUENT C.

Oct., Nov., Dec., 1907...	149	53	112	58	54	22.8	5.3	2.2	13.6	0.2	2.5	38	30	7.3	5.6	7.8	28	46
Jan., Feb., Mar., 1908...	139	37	173	132	41	27.6	6.9	2.9	15.0	0.1	2.7	48	37	8.2	6.4	8.8	27	37
Apr., May, June, 1908...	202	109	292	194	98	40.3	13.5	7.0	14.8	0.5	4.5	66	40	15.4	8.0	5.8	46	55
July, Aug., Sept., 1908...	120	77	106	63	43	24.0	7.7	4.3	7.6	1.0	3.4	42	31	3.9	5.9	5.4	58	68
Oct., Nov., Dec., 1908...	144	97	95	68	27	23.9	6.7	3.2	7.8	0.7	5.5	36	26	7.7	4.8	6.8	75	47
Jan., Feb., Mar., 1909...	161	118	102	72	30	28.1	6.8	4.5	8.2	0.5	8.1	29	16	6.9	4.0	7.1	76	40
Apr., May, 1909........	315	242	101	55	46	62.9	26.2	17.1	13.2	0.1	6.3	52	25	11.5	5.6	5.3	50	50

EFFLUENT D.

Oct., Nov., Dec., 1907, Jan., Feb., 1908.........	136	36	57	40	17	27.4	4.8	3.3	14.9	0.5	3.9	44	39	8.0	6.4	8.2	33	42

NEW FILTER D.

Mar.,Apr.,May,June,1908.	171	65	238	189	49	35.7	10.4	6.6	16.6	0.3	1.8	60	43	11.6	7.7	6.4	26	50
July, Aug., Sept., 1908...	133	68	117	71	46	24.1	7.2	5.5	7.3	1.3	2.8	43	33	9.7	7.1	5.0	41	67
Oct., Nov., Dec., 1908...	153	95	130	91	39	27.6	7.3	4.4	10.1	1.1	4.7	39	28	8.6	5.3	6.6	45	47
Jan., Feb., Mar., 1909...	173	107	107	78	29	31.7	9.2	5.5	11.7	0.8	4.5	29	19	7.7	4.9	6.8	29	39
Apr., May, 1909........	246	167	118	70	48	35.4	9.5	5.0	15.7	0.2	5.0	54	30	11.7	6.7	4.0	37	50

EFFLUENTS A AND B SETTLED.

Oct., Nov., Dec., 1907...	120	37	68	37	31	22.8	3.7	1.9	14.6	0.1	2.5	35	34	5.2	3.6	...	45	..
Jan., Feb., Mar., 1908...	118	29	168	143	25	28.2	6.5	3.1	14.1	0.4	4.1	45	40	6.3	5.3	...	..	..
Apr., May, June, 1908...	109	46	87	71	16	27.3	5.9	3.4	11.9	0.7	5.4	42	35	7.5	5.3	...	..	..
July, Aug., Sept., 1908...	63	33	40	39	1	19.3	4.5	3.6	6.7	0.8	3.7	32	28	5.7	4.9	...	..	..
Oct., Nov., Dec., 1908...	84	59	52	35	17	19.5	3.6	1.9	6.9	0.7	6.4	27	22	4.9	3.7	...	91	..
Jan., Feb., Mar., 1909...	83	55	49	38	11	26.5	4.8	3.4	7.8	0.5	10.0	22	15	4.3	3.4	...	94	..
Apr., May, 1909.........	126	104	55	41	14	29.8	5.1	3.9	9.4	0.4	11.0	33	25	6.1	4.4	...	96	..

EFFLUENTS C AND D SETTLED.

Oct., Nov., Dec., 1907...	128	41	...	...	...	22.6	3.7	2.2	13.9	0.2	2.6	37	35	7.3	5.8	...	31	..
Jan., Feb., Mar., 1908...	125	27	114	91	23	28.1	4.8	2.9	15.9	0.3	4.2	47	41	7.4	6.3	...	27	..
Apr., May, June, 1908...	109	39	98	75	23	32.9	8.8	5.2	15.6	0.5	2.8	45	39	8.8	6.8	...	36	..
July, Aug., Sept., 1908...	59	33	54	44	10	23.1	7.0	4.8	7.0	1.2	3.1	36	30	6.2	5.3	...	59	..
Oct., Nov., Dec., 1908...	85	63	40	34	6	20.1	3.9	2.3	7.9	0.7	5.3	28	24	5.0	3.7	...	71	..
Jan., Feb., Mar., 1909...	83	55	49	38	11	26.9	4.8	3.4	7.8	0.5	10.4	22	15	4.3	3.3	...	59	..
Apr., May, 1909........	127	104	55	41	14	30.0	5.1	3.9	9.4	0.4	11.2	37	25	6.1	4.4	...	40	..

TABLE 2.

AVERAGE ANALYSES OF SEWAGE TRICKLING EFFLUENTS AND SEDIMENTATION EFFLUENTS FOR THE ELEVEN MONTHS, JULY, 1908—MAY, 1909.

Parts per Million.

	Suspended Solids			Nitrogen as						Oxygen Consumed				Dissolved Oxygen	Relative Stability
					Organic					30′ Boiling		15′ Cold			
	Total	Vol.	Fixed	Total	Tot.	Sol.	NH_3	N_2O_3	N_2O_5	Tot.	Sol.	Tot.	Sol.		
Sewage	133	101	32	31.7	9.8	6.6	14.7	0.1	0.6	57	38	11.8	8.0	2.2	....
Eff. A	111	75	36	27.8	9.0	5.0	6.8	0.5	5.7	39	25	8.2	4.9	8.1	86
Eff. B	106	63	43	27.3	7.8	4.4	7.9	0.6	6.6	39	25	8.1	4.8	7.4	88
Eff. C	101	64	37	34.7	11.8	7.3	9.2	0.6	5.8	40	24	7.5	5.1	6.1	65
Eff. D	118	77	41	29.7	8.3	5.1	11.2	0.8	4.2	41	27	9.4	6.0	5.6	38
A–B settled	49	38	11	23.8	4.5	3.2	7.7	0.6	7.8	28	22	5.2	4.1	....	94
C–D settled	49	39	10	25.0	5.2	3.6	8.0	0.7	7.5	30	23	5.4	4.2	....	57

points about the chemical figures. The free ammonia values for effluents are distinctly affected by the size of material and depth of filter. The reductions in this constituent were 54 per cent, 46 per cent, 37 per cent, and 24 per cent respectively for A, B, C, and D. The other noticeable difference lies in the soluble oxygen consumed as determined in the cold. Instead of a purification of 40 per cent as shown by Filters A and B, and 36 per cent for Filter C, Filter D only decreased this constituent by 25 per cent. The oxygenation of Effluents C and D was distinctly less than for A and B.

The main difference between the effluents is, however, brought out only by a comparison of the figures for stability. The quarterly averages for this determination are brought together for comparison in Table 3 and are plotted in Figure 1. The data were obtained by daily tests by the methylene blue method and the relative stability number is derived from a scale in which a stability of 21 corresponds to decolorization in 1 day, 37 to decolorization in 2 days, 50 to decolorization in 3 days, 60 to decolorization in 4 days, 68 to decolorization in 5 days, 75 to decolorization in 6 days, 80 to decolorization in 7 days, 90 to decolorization in 10 days, and 96 to decolorization in 14 days, all at 70° F. (Phelps, 1909). Any value over 75 may be considered reasonably satisfactory.

During the first six months of operation in the autumn and winter of 1907–8 the bacteria did not begin active work in the filters and all the effluents were putrescible, losing their oxygen in less than 2 days.

In the spring of 1908, A and B, the 8-foot stone filters, began to improve, and for the last year of operation neither of them showed a quarterly average below 80. In other words these effluents stored

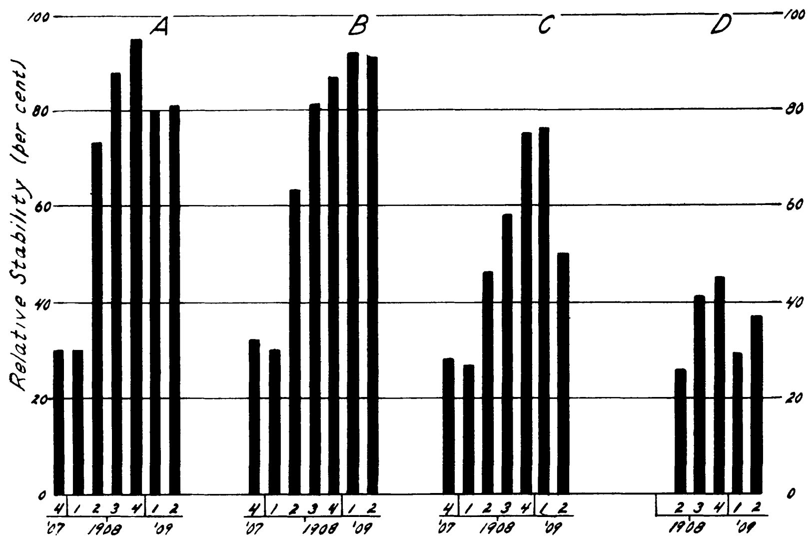

FIG. 1.—Relative stability, quarterly averages, filters A, B, C, and D.

in closely stoppered bottles contained oxygen enough to last for over a week, a condition which could scarcely cause a nuisance in a natural water course under any conceivable circumstances. There was little choice between these two effluents during this period, A being a little more stable in 1908 and B a little better in 1909.

TABLE 3.

RELATIVE STABILITY OF TRICKLING AND SEDIMENTATION EFFLUENTS.

Quarterly Averages.

	1907		1908			1909	
	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Effluent A	30	30	68	88	95	80	81
Effluent B	32	30	63	81	87	92	91
Effluent C	28	27	46	58	75	76	50
Effluent D	..	29	25	41	45	29	37
A–B settled	45	..	..	..	91	94	96
C–D settled	31	27	36	59	71	59	40

Filter C, on the other hand, with only 5 feet of depth, gave distinctly inferior results. In every quarter its effluent was less stable

than those of the 8-foot beds. During the autumn and winter of 1908–9 it yielded an effluent of barely passable quality (75), but with the discharge of suspended solids in the spring, the stability fell again to 50. It seems clear that a bed of this character cannot be relied upon to yield a satisfactory effluent.

The open brick bed was unable to produce a stable effluent under the conditions of the experiment. Its stability figure varied between 30 and 45 when it was at its best, decolorizing in 2–3 days. It is somewhat remarkable perhaps that such a crude mechanism should have operated even as well as it did. The attainment of an effluent stable for 2 days even is a notable achievement for a process in which sewage runs rather rapidly over a structure of open brickwork with no filtering action whatever.

3. *Conclusions in regard to depth of beds and size of filtering materials.*—The first general conclusion to be drawn from these experiments concerns the size of the filtering material. The use of fine filling has been urged by many engineers in England. In testifying before the Royal Commission, Garfield, Ducat, and Corbett all fixed the size of stone for trickling beds at values less than one inch (Martin, 1905), and both Barwise (1904) and Raikes (1908) express similar opinions. This sort of material, however, requires very careful preliminary treatment. In America the comparative weakness of the sewage makes such fine material unnecessary and it is possible to use coarse beds and allow more suspended matter to pass upon them. Both at Reading and Columbus the filling material is over $1\frac{1}{4}$ inches in diameter.

The brief experience with Filter D when it was filled with $\frac{1}{2}$-inch stone showed that the treatment of crude Boston sewage on a bed of this kind was quite out of the question on account of the resultant clogging. A comparison of Filters A and B made it apparent that, with the particular sewage we were working with, $1\frac{1}{2}$ inches was the lower limit for practical efficiency. Filter A was of 1 to $1\frac{1}{2}$-inch, Filter B was of $1\frac{1}{2}$ to 2-inch stone. The analytical data, as indicated in Table 2, were practically identical for the two beds. In fact Filter B was a little the better in all respects, except as regards free ammonia and dissolved oxygen. Filter A however gave considerable trouble from clogging, while Filter B kept in good condition

with only a reasonable amount of care. $1\frac{1}{2}$ to 2-inch stone may therefore be considered the most suitable material for the purification of sewage like that of Boston.

Granting this premise a comparison of Filters B and C makes it possible to draw a fairly definite conclusion in regard to the relation between depth and efficiency in purification. Filter B had about 7 feet of effective filtering material over the underdrains, Filter C about 4 feet. Filter C had the advantage of somewhat better distribution from a siphon tank. Reference to Table 2 shows that in regard to suspended solids and oxygen consumed there was little or no choice between the beds. Organic nitrogen, particularly in the soluble form, was very much higher in Effluent C. Free ammonia was slightly higher and dissolved oxygen slightly lower. The main difference, however, was in the stability. The great delicacy of the methylene blue reaction is well shown here. Analytical differences between the two effluents are too slight to permit a very sharp distinction between them. Yet the methylene blue test shows that Effluent B had an average stability of over 80 for the last year of operation, and Effluent C rose to 75 only in the cold autumn and winter months, was under 60 in the summer, and fell to 50 in the spring of 1909. Thus the average reducing time for Effluent B was always over a week, while that for Effluent C fell for the spring quarter to 3 days, a decidedly unsatisfactory result.

It may be concluded then that beds of broken stone treating sewage like that with which we worked must be in the neighborhood of 7 feet deep (exclusive of underdrains) in order to insure an effluent having 80 per cent relative stability, a reasonable requirement under local conditions.

4. *The cycle of suspended solids.*—It was noted in our earlier work (Winslow and Phelps, 1907), as it has been observed at Birmingham, England (Watson, 1910), and elsewhere, that the suspended solids in trickling filter effluents exhibit a very marked and characteristic seasonal cycle. The results of the 1905–7 studies and of the present experiments are plotted together for comparison in Fig. 2. In each of the four years represented on the plot there is indicated a great increase in suspended solids during the spring

quarter, the total suspended solids being doubled or tripled in amount. The trickling bed accumulates suspended matter during nine months of the year and discharges its accumulation in the other three. The process begins with the first onset of warmer weather in March or April and culminates in May. The cycle appears to be as constant and regular as any other seasonal biological phenomenon, and it must be reckoned with practically in connection with the effect of a trickling effluent upon the body of water into which it is discharged.

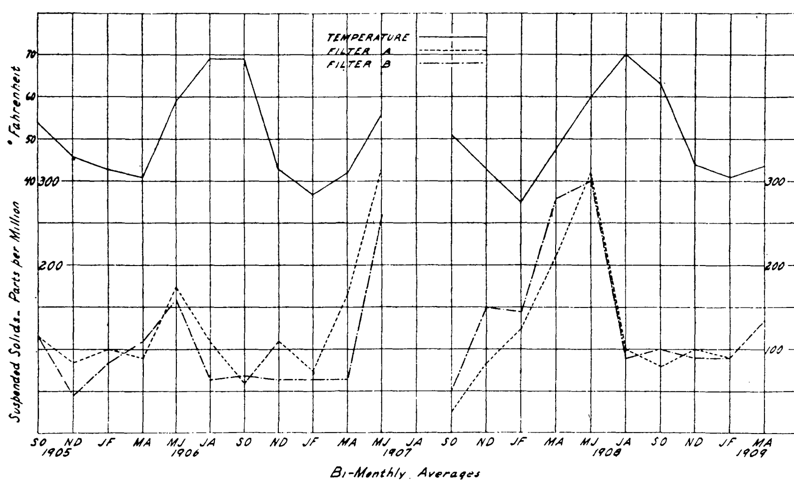

FIG. 2.—Relation between temperature and suspended solids in trickling filter effluents, Sewage Experiment Station of the Massachusetts Institute of Technology.

It must be noted, however, in connection with the character of this spring discharge that the increase in fixed solids is much greater than in the volatile constituents (see Table 1).

5. *Sedimentation of trickling effluents.*—In spite of the stability of the trickling effluents, the presence of more than 100 parts of suspended solids would be likely to cause obnoxious sludge deposits if the effluent were discharged into water where there was not a rather vigorous current. The effluents were therefore submitted to secondary sedimentation for a period of about two hours in the conical tanks described above.

The character of the resulting effluents is indicated in Table 2. Total suspended solids were reduced by 55 per cent, volatile suspended solids by 45 per cent, and fixed suspended solids by 72 per cent (comparing the average of Effluents A and B with the mixed settled effluent). A rather notable feature of the analyses is the marked reduction in soluble organic nitrogen, the appreciable reduction in soluble oxygen consumed, and the definite increase in nitrates. It is clear that during the brief storage period in the tanks the aerobic changes initiated in the filter were continued, leading to further organic purification, aside from the physical effect of sedimentation. This is an interesting indication of the excellent character of the trickling effluents themselves. The sedimented effluents were of course rendered more stable than before treatment, the figure for A and B rising from an average of 87 to 94 and for C and D from an average of 51 to 57.

The amount and character of the sludge removed from the secondary sedimentation tanks is indicated below in Table 4, for all seven quarters in the case of Effluents A and B and for the last three quarters in the case of Effluents C and D.

The volume of sludge produced varied from 3 to 12 cubic yards per million gallons of sewage treated, excluding the first two quarters, in which the discharge of suspended matter was of course comparatively small. The high figures, 6 to 12 cubic yards, occurred in the spring quarters, resulting from the annual discharge of suspended solids at that season.

The disposal of the sludge from this process remains of course a serious problem, as indeed is the case in all methods of sewage disposal. Experiments have been conducted at the station looking toward the disposal of this sludge along two principal lines. In one investigation the sludge was treated in a sort of intensive septic tank in the hope that liquefaction might reduce the amount to be handled. In another investigation the sludge was pressed and a study was made in regard to its possible fertilizing value. Neither line of work yielded encouraging results, and it appears probable that dumping at sea, digging into the land, or pressing and burning remain the most satisfactory methods of sludge disposal.

II. THE PURIFICATION OF SEWAGE BY INTERMITTENT FILTRATION AT HIGH RATES, AFTER PRELIMINARY REMOVAL OF SUSPENDED SOLIDS IN A BIOLYTIC TANK.

(WITH NOTES ON SOME EXPERIMENTS BY J. H. WHITE.)

In Massachusetts, the home of the intermittent sand filter, it has been the general practice to purify sewage at comparatively low rates. The original studies at the Lawrence Experiment Station pointed to a rate of about 100,000 gallons per day as a probable maximum, and in actual operation few of the plants in the eastern states have ever reached this figure. The data recorded by the Massachusetts State Board of Health six years ago (Mass., 1904) were as follows: Stockbridge, 20,000 gallons per acre per day; Andover, Clinton, and Framingham, between 30,000 and 40,000; Brockton, Southbridge, and Spencer, between 40,000 and 50,000; Natick, 50,000; Hopedale and Pittsfield, between 60,000 and 70,000; Westboro, 70,000; Leicester, 80,000; Concord and Marlboro, between 90,000 and 100,000; Gardner and Worcester, between 120,000 and 130,000.

It is apparent however that no such limit as this is necessarily set by the essential nature of the process, so far at least as nitrification goes. A dose of 100,000 gallons an acre corresponds to a depth of less than four inches of sewage. With a clean bed of fairly coarse sand, well leveled and equipped with good distributors, such a dose disappears in half an hour and may be repeated once every six hours without interfering at all with nitrification. A few hours is ample for the bacterial processes of purification, as indicated by numerous laboratory experiments like those of Scott-Moncrieff (1899) at Ashtead and of Calmette and his associates at Lille (Rolants and Gallemand, 1901). The difficulty in the practical operation of intermittent filters at high rates arises from the clogging of the surface layers with suspended solids. The period for which the sewage remains on the surface of the beds is gradually prolonged as the clogging increases, until finally a new dose can be applied only after a long interval. In summer this condition can be avoided without any serious difficulty. If sewage is applied at a rate of 400,000 gallons instead of 100,000, sludge deposits on the surface accumulate four times as fast, while for

TABLE 4.

SLUDGE DATA.

Average of Months	Total Vol. of Sludge in Gals.	Sp. Gravity	Grams per 100 c.c.							Total Volume of Sewage in Gals.	Sludge per Million Gals. of Sewage in Cu. Yds.	Pounds per Million Gallons of Sewage						
			Suspended Solids			Organic Nitrogen		Organic Carbon by Permanganate				Suspended Solids			Organic Nitrogen		Organic Carbon by Permanganate	
			Total	Vol.	Fixed	Total	Susp.	Total	Susp.			Total	Vol.	Fixed	Total	Susp.	Total	Susp.
SLUDGE FROM COMBINED EFFLUENTS OF FILTERS A AND B.																		
Oct., Nov., Dec., 1907	60	1.02	8.44	4.78	3.66	...	0.165	....	0.357	240,000	1.29	188	111	77	....	3.5	....	5.6
Jan., Feb., Mar., 1908	102	1.03	9.04	5.38	3.66	...	0.181	....	0.391	252,000	2.59	275	169	106	....	5.8	....	13.1
April, May, June, 1908	406	1.03	9.30	2.11	7.19	...	0.213	....	0.450	296,000	6.37	1,275	497	778	....	24.0	....	48.1
July, Aug., Sept., 1908	176	1.03	8.22	3.54	4.63	...	0.31	....	0.51	221,000	3.90	522	223	299	....	18.0	....	29.8
Oct., Nov., Dec., 1908	246	1.04	8.55	4.36	4.19	0.41	0.40	0.55	0.54	220,000	3.78	545	277	268	25.3	25.0	36.5	36.2
Jan., Feb., Mar., 1909	401	1.05	6.57	3.78	2.89	0.31	0.30	0.42	0.40	389,000	5.27	490	274	216	26.8	26.1	43.1	39.0
Apr., May, 1909	440	1.05	....	....	....	0.29	0.29	0.67	0.67	172,000	12.64	....	...	....	36.3	36.3	84.0	84.0
SLUDGE FROM COMBINED EFFLUENTS OF FILTERS C AND D.																		
Oct., Nov., Dec., 1908	210	1.04	7.6	4.2	3.3	0.27	0.26	0.50	0.49	266,000	3.98	496	281	214	18.7	17.8	32.4	31.9
Jan., Feb., Mar., 1909	176	1.04	6.1	3.2	2.9	0.30	0.29	0.38	0.37	300,000	3.07	260	138	122	13.7	13.4	19.2	18.9
April, May, 1909	199	1.04	...	...	...	0.49	0.49	0.54	0.53	163,000	6.35	....	...	....	24.0	24.0	26.4	26.0

successful operation at the high rate the beds cannot be allowed to clog to the extent which would be quite permissible with daily dosing. It is simply necessary, however, to remove the sludge deposit more frequently from a smaller area; and it is probably quite as economical to scrape a ton of sludge from one acre as from two. It is in winter however that difficulty arises. The surface of the beds cannot be reached during the coldest weather, the beds clog, more area is required, and the whole plant must be designed for this condition of excessive strain. When crude sewage is applied to poorly leveled beds, being allowed to flow on as it will without dosing tanks to secure efficient distribution, there seems no hope of securing better results.

In the middle western states, however, intermittent filters have been constructed which appear to be of a more intensive and efficient type. Individual beds are small and carefully leveled; sewage is applied from dosing tanks automatically discharged at frequent and regular intervals; and the sewage is prepared for treatment by the preliminary removal of a considerable proportion of its suspended solids. If we are correct in our conclusion that the clogging of beds in winter is the factor which limits the efficiency of the intermittent filter, preliminary treatment would seem clearly indicated as a rational remedy. At several of the middle western plants rates of 400,000 gallons per acre per day are claimed under this system of operation. Notable examples of such filters are to be seen for instance in the town of Wauwatosa, Wis. The town plant (100,000 gallons) and the County Institutions plant (400,000 gallons) both include septic tanks for preliminary removal of suspended solids, both are dosed several times in the twenty-four hours from automatic dosing tanks, and both operate at a rate of 400,000 gallons per acre per day. The County plant when seen by one of the writers five years ago (Winslow, 1905) was in excellent condition and was yielding an effluent of good appearance. Unfortunately no analyses are obtainable from either of these plants. The septic tank and intermittent filter combination installed by Mr. F. A. Barbour (1905) at Saratoga, N.Y., is designed on the same general plan but is operated at a rate of only 60,000 gallons per acre per

day. Mr. Barbour believes, however, that this rate could be greatly increased if the amount of sewage demanded it.

In some of our earlier experiments (Winslow and Phelps, 1906), we made a study of the operation of sand filters at high rates, with unexpected success. The experimental filters were cypress tanks, 6 feet by 4 feet, filled with 2 feet of sand over 6 inches of gravel underdrainage. The sand had an effective size of 0.17 mm. and a uniformity coefficient of 3.5. The filters were in a covered shed and were thus protected from the severity of the weather, the quarterly average temperature never falling below 39° F. Crude sewage was applied to Filter 1, and septic effluent to Filters 24 and 25. Filter 1 was started in June, 1903, at a rate of 100,000 gallons per acre per day, but the rate was doubled in December and doubled again in June, 1904, being then maintained at 400,000 gallons till the close of the experiments in May, 1905. Filters 24 and 25 were put in operation in March, 1904, and operated consistently at 400,000 gallons per acre per day. The analytical results from all three filters were excellent, as indicated in Table 5. The care of the surface was not serious. Filter 1 was scraped three times and raked once, Filter 24 was raked twice, and Filter 25 was raked once and scraped once.

TABLE 5.

RESULTS OF INTERMITTENT FILTRATION AT HIGH RATES. INDOOR FILTERS. 1904–5.

Parts per Million.

	Filter 1	Filter 24	Filter 25
Nitrogen as Alb. NH_3	0.6	0.6	0.7
Nitrogen as Free NH_3	5.4	4.0	4.9
Nitrogen as Nitrites	0.3	0.3	0.2
Nitrogen as Nitrates	23.9	21.3	18.8
Oxygen consumed	6.8	6.5	6.4
Oxygen dissolved	6.3	7.4	7.5

When the new experimental plant for the Sanitary Research Laboratory was built at Old Harbor Point (Winslow and Phelps, 1910), we were anxious to make a test of the possibility of treating sewage on sand filters at high rates on a more practical scale. We therefore constructed an outdoor sand bed of about 500 square feet in area to be operated under normal weather conditions. A general view of the bed is shown in Fig. 3.

The sand bed is 21×22 feet in plan and was built on the old brick floor of a ruined building, once a portion of the garbage reduction plant, the walls and foundation of which were utilized in the construction of the filters. For underdrains, 4-inch half-round tile pipes were laid in four channels in the brick floor. The filtering layer is 3.5 feet deep of beach sand, from the immediate vicinity, with an effective size of 0.36 mm. and a uniformity coefficient of 1.9.

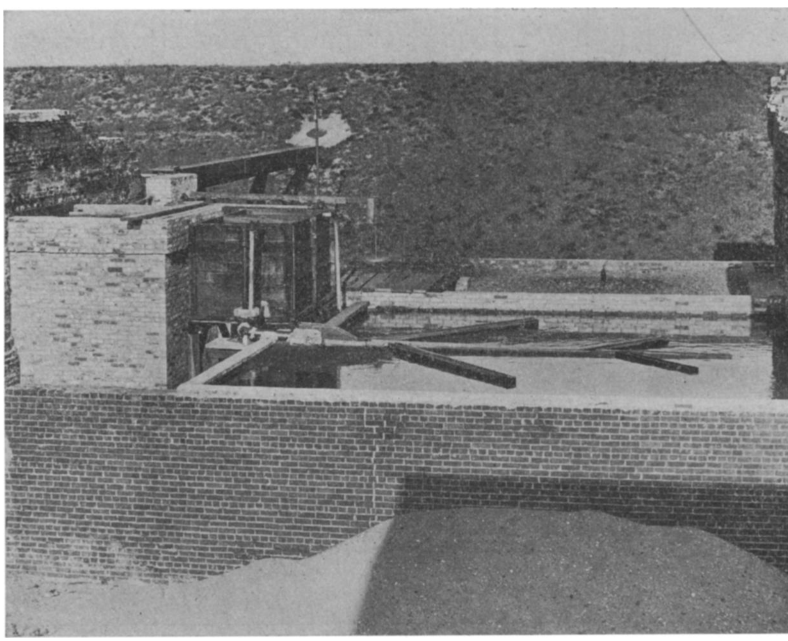

FIG. 3.—View of sand filter bed, Sewage Experiment Station of the Massachusetts Institute of Technology, 1909.

The sewage is distributed on the bed from a dosing tank holding 850 gallons, which at the theoretical rate would discharge about once in 5 hours, giving a rate of 4,250 gallons, or approximately 400,000 gallons per acre per day. The sewage is distributed on the bed by a system of wooden troughs, shown in Fig. 3, with 1-inch outlets, spaced 6 inches apart. The effluent from the sand filter passes from the underdrains to cement channels in an arched brick tunnel under the floor, which serves as a sampling chamber.

The tank used for the preliminary treatment of the sewage to

be applied to the sand filter is of a somewhat peculiar type, and to distinguish it from the ordinary septic tank we have called it a biolytic tank.

The actual removal of suspended solids is of course accomplished in almost all preliminary processes by the simple physical action of sedimentation. The proportion of suspended solids thus removed is usually between 50 and 65 per cent with American sewages (Fuller, 1909), although in England and Germany considerably higher results have been reported. The septic tank was originally designed not to improve the removal of suspended solids but to eliminate by liquefaction a portion of the material deposited. The early claims to the effect that 75 to 80 per cent of the deposited sludge could be thus liquefied have not, however, been generally substantiated. Most of the septic tanks which have been carefully studied, both in England and in the United States, have liquefied between 25 and 40 per cent of the suspended solids which they removed. At certain plants, as at Birmingham, England, values as low as 10 per cent have been recorded.

In considering the limitations of the septic process which cause it to stop so far short of complete decomposition it seemed probable that the accumulation of waste products from the process itself might be one of the principal factors in checking its progress. This is a common phenomenon in all bacteriological reactions, the removal of the end-products being almost invariably a necessary condition for continued activity. An experiment made some years ago at the Lawrence Experiment Station is suggestive of such an action, since it indicates that a shorter storage period tends to facilitate liquefaction and a shorter storage period means less accumulation of waste products. A small septic tank was dosed, not with sewage, but with the more concentrated sludge from settled sewage. For six months the storage period was from five to fifteen days, and sludge accumulated, filling up 60 per cent of the tank. The rate was then increased, so that the storage period was reduced to 49 hours, when the accumulated sludge decreased to 8 per cent and did not further increase for a year (Massachusetts, 1901). At Leeds it was found that a 72-hour septic period interfered with the solution of sludge (Leeds, 1905).

In some of our own earlier experiments (Winslow and Phelps, 1906) we found that sludge liquefaction was much more active with a 12-hour period than with a 24-hour period and more active with a 24-hour period than with one of 48 hours.

In the spring of 1909, at the suggestion of one of the writers, Mr. J. H. White made a laboratory study of this problem which tended to confirm these conclusions. Mr. White took two 3-liter bottles, A and B. Into A was poured 1,000 c.c. of sewage sludge and 1,000 c.c. of tap water, into B 1,000 c.c. of sludge alone. Bottle A was fitted with an inlet tube by which fresh tap water could be admitted through a stopcock, an outlet tube discharging by a siphon into a second stoppered bottle, a gas outlet through which the accumulated gas could be discharged, and a mercury gage to measure gas pressure. Bottle B was fitted with a gas outlet and pressure gage alone. Both were tightly sealed with sealing-wax and paraffin.

Daily observations were made of the temperature and pressure in each bottle and the gas was then allowed to escape. Each day 200 c.c. of fresh tap water was added to Bottle A and 200 c.c. of the contained liquid siphoned off. The sludge was analyzed at the beginning of the experiment and the contents of both bottles at the close; and weekly analyses were made of the effluent from Bottle A. Vigorous septic action took place in both cases, as manifested by the formation of scum and the production of gas bubbles. The fermentation in both bottles continued to the end of the experiment (33 days).

Mr. White calculated from his analyses the actual amount of various constituents in the original sludge, in the contents of Bottle A at the end plus the effluents from Bottle A, and in Bottle B at the end. The results, as shown in Table 6, indicate very clearly that the liquefying processes were markedly favored by the flushing out with fresh tap water. Bottle A yielded more than twice as much organic nitrogen in solution, free ammonia, and fixed solids in solution and nearly twice as much volatile solids in solution, as compared with Bottle B. It left, on the other hand, only 8.66 gms. of volatile solids in suspension against 14.20. Fixed solids in suspension were increased in the A effluent.

If our conclusions are justified and the limitations of the liquefying activity of the ordinary septic tank are due to the accumula-

tion of toxic waste products, the Hampton hydrolytic tank and the Imhoff deep tanks used in West Germany are designed on a principle that is not favorable to sludge liquefaction. In both these tanks the sludge is separated from the flowing sewage and stored in a liquefying chamber where it is subjected to intensive septic action with a minimum of opportunity for the removal of end-products. We have attempted to secure precisely the opposite result by using the deep conical tank with an inflow at the bottom and an outflow at the top, the sludge being constantly washed in a

TABLE 6.

RESULTS OF SEPTIC TREATMENT WITH AND WITHOUT FLUSHING.

(Experiments made by J. H. White.)

	Sludge before Treatment	Contents of Bottle A + Effluent	Contents of Bottle B
Nitrogen (parts per million):			
Total organic	1,300	1,504	1,200
Organic in solution	120	560	188
Free Ammonia	49	386	144
Solid (gms.):			
Total	35.20	34.64	31.20
Total in solution	6.00	13.74	7.40
In suspension	29.20	20.90	23.80
Volatile:			
Total	17.90	14.08	17.60
In solution	2.12	5.42	3.40
In suspension	15.78	8.66	14.20
Fixed:			
Total	17.30	20.56	13.60
In solution	3.88	8.32	4.00
In suspension	13.42	12.24	9.60

current of fresh sewage so that the products of decomposition may be removed. The tank is essentially like the Dortmund tank used for many years for sedimentation of sewage. Tanks of this general pattern are in operation with great success at Birmingham, England (Watson, 1910). So far as we are aware, however, all such tanks have hitherto been used for plain sedimentation, the sludge being removed too frequently to permit of septic action. In the case of our tank no sludge has been removed for a year and septic processes were obviously active. On the other hand, as the essential principle of the septic tank is recognized to be the retention of the sewage so as to promote anaerobic conditions as far as possible, while our aim is to limit these conditions, this tank is hardly a septic tank in the ordinary use of the term and might better be called a biolytic tank.

The tank itself is square at the top, and 7 feet across (see Fig. 4). The vertical sides extend downward for 2.5 ft., below which the walls converge to form a hopper. They have a slope of about 55 degrees with the horizontal. The capacity is 1,540 gals., and the flow period 8.5 hrs. The sewage enters through a 2-inch pipe about 9 inches from the bottom and the effluent is skimmed off at the surface by four 60-degree triangular metal weirs, placed at the

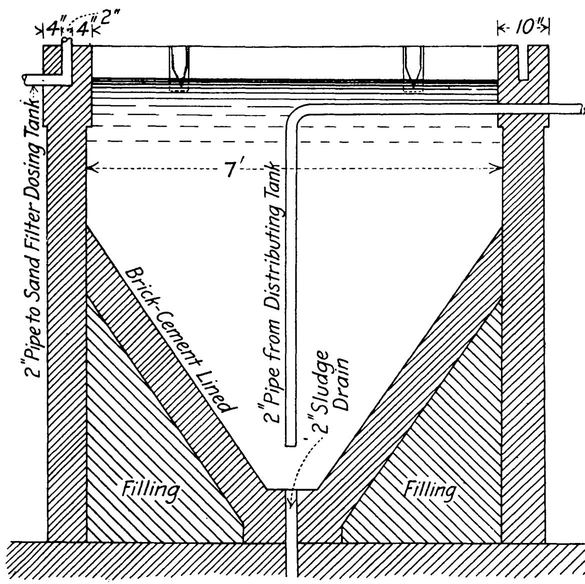

FIG. 4.—Cross-sectional view of biolytic tanks, Sewage Experiment Station of the Massachusetts Institute of Technology.

corners and discharging into 2-inch channels in the walls. Scum-boards protect these weirs. At the bottom of the tank is a 2-inch effluent drain for sludge.

The biolytic tank was first put in operation in July, 1909, and has since been in continual use, for six days in the week, and for seven days during the colder months. Samples are collected from all parts of the experimental plant every three hours, and the samples are mixed, chloroformed, and analyzed once a week. The analytical methods used include determinations of turbidity and

sediment, suspended matter, nitrogen as free ammonia, nitrites, nitrates and total Kjeldahl, oxygen consumed, total and dissolved, by both the 30-minute boiling and the 15-minute room temperature method.

The general character of the crude sewage is indicated by the monthly averages in Table 7. It represents the mixed sewage from the entire South Metropolitan District of Boston (about 90 million gallons a day), after screening through coarse bar screens at the city pumping plant and the removal of heavy grit in a small detritus chamber at our own station. The sewage of Boston is rather weak for the sewage of a large American city, particularly as regards suspended solids and free ammonia.

TABLE 7.

COMPOSITION OF CRUDE SEWAGE.

Monthly Average of Weekly Composite Samples.

MONTH 1909–10	TURBIDITY	SEDIMENT	SUSPENDED SOLIDS			NITROGEN AS						OXYGEN CONSUMED			
							Organic					30′ Boiling		15′ Cold	
			Total	Vol.	Fixed	Total	Total	Sol.	Free NH_3	N_2O_3	N_2O_5	Total	Sol.	Total	Sol.
August	305	150	156	130	26	29.5	13.1	6.7	16.2	.1	.1	73	53	19.3	12.0
September	420	280	212	145	67	30.0	14.8	9.3	14.8	.0	.0	68	39	17.4	8.9
October	335	220	139	109	30	24.0	9.0	3.8	14.9	.2	.1	70	49	15.8	12.9
November	340	220	184	139	45	27.0	9.5	6.1	17.5	.1	.3	76	47	17.1	9.6
December	315	190	112	74	38	27.0	14.0	7.3	12.1	.1	.3	56	40	14.2	8.1
January	290	160	114	76	38	18.0	7.7	5.3	8.7	.1	1.2	65	46	12.0	7.1
February	405	190	180	100	80	21.0	13.4	10.9	6.6	.1	.8	74	58	13.7	9.2
March	240	160	200	....	....	23.0	11.3	7.8	10.0	.1	1.2	59	35	12.9	8.9
April	340	230	150	100	50	30.0	15.5	13.3	13.3	.1	1.2	74	49	18.1	12.4
May	370	205	180	120	60	24.0	9.2	7.0	18.0	.1	.2	85	72	20.0	12.9
Average	365	200	163	110	48	25.3	11.7	7.7	13.2	.1	.5	70	49	16.0	10.2

Marked seasonal variations are apparent in free ammonia and in oxygen consumed as determined in the cold, both values falling during the winter months and rising as increasing temperatures facilitate bacterial action. Suspended solids are low during the freezing weather of December and January and rise again with the spring thaws.

The work of the biolytic tank in regard to the removal of sus-

pended solids may be estimated by comparing the analyses of its effluent for the corresponding period as they are given in Table 8.

TABLE 8.

COMPOSITION OF EFFLUENT FROM THE BIOLYTIC TANK. MONTHLY AVERAGES OF WEEKLY COMPOSITE SAMPLES.

Parts per Million.

Month 1909–10	Turbidity	Sediment	Suspended Solids			Nitrogen as						Oxygen Consumed			
							Organic					30′ Boiling		15′ Cold	
			Total	Vol.	Fixed	Total	Total	Sol.	Free NH_3	N_2O_3	N_2O_5	Total	Sol.	Total	Sol.
August	165	55	77	69	8	24	6.7	3.6	17.2	.0	.1	53	39	18.0	15.7
September	230	120	123	92	31	27	11.1	6.4	16.1	.0	.0	56	35	17.0	11.3
October	200	110	88	74	14	21	5.3	4.5	15.5	.0	.0	57	37	15.5	12.2
November	195	105	59	49	10	23	6.1	5.0	16.4	.0	.0	55	40	15.0	12.3
December	185	75	70	45	25	23	8.9	4.4	14.3	.0	.0	53	39	14.1	10.6
January	210	100	70	40	30	18	7.2	5.0	9.5	.2	.7	49	35	11.5	8.2
February	260	120	90	60	30	19	8.6	4.1	9.9	.1	.4	49	37	11.4	7.7
March	240	125	90	..	..	21	8.6	6.4	12.1	.1	.1	47	28	14.1	11.0
April	180	100	70	50	20	25	6.0	5.8	18.5	.0	.0	60	40	20.8	17.5
May	175	75	70	50	20	23	6.4	6.0	16.6	.0	.0	65	44	24.4	21.9
Average	204	98	81	58	21	22	7.5	5.1	14.6	.0	.1	54	37	16.2	12.8

Comparison of the final averages in Tables 7 and 8 shows the usual changes, characteristic of septic action. Free ammonia was increased from 13.2 parts to 14.6 parts; and of the unstable carbonaceous compounds determined by oxygen consumed in the cold the soluble portion was increased from 10.2 parts to 12.8 parts. Of the organic nitrogen, the suspended portion was reduced from 4.0 parts to 2.4 parts (40 per cent), and the dissolved portion from 7.7 parts to 5.1 parts (34 per cent). The oxygen consumed determined at 212° F. showed similar decrease from 21 to 17 (19 per cent) for the suspended portion and from 49 to 37 (24 per cent) for the dissolved portion.

The principal changes, however, were of course in the suspended matter. The sediment was reduced from 200 to 98 (51 per cent); the total solids from 163 to 81 (50 per cent); the volatile portion from 110 to 58 (47 per cent); and the fixed portion from 48 to 21 (56 per cent). These results correspond pretty well with those obtained from good septic tanks in actual practice, as indicated in Table 9, compiled from the final report of the British Royal Commission (1908) and from the results of certain American tanks.

TABLE 9.

REDUCTION OF SUSPENDED SOLIDS BY SEPTIC TREATMENT.

Plant	Per cent Reduction	Plant	Per cent Reduction
Andover, England	30	Hartley Wintney, England	54
Slaithwaite, England	34	Knowle, England	57
Worcester, Mass	35	Saratoga, N.Y.	65
Prestolee, England	42	Exeter, England	67
Caterham, England	47	Reading, Pa	74
Columbus, Ohio	49	York, England	75
Accrington, England	50	Rochdale, England	86
Boston, Mass	50		

The variations at different plants are of course very great, since both the nature of the sewage and the construction of the tanks influence the end result. Seven of the other fourteen plants recorded, however, show a purification less than that effected by our tank, while the other seven yielded better results. This seems a good showing in view of the fact that the weakest point in a deep continuous-flow tank lies in its tendency to discharge too much of the suspended matter it receives.

In regard to the other requisite in a successful tank, the liquefaction of the deposited solids, the biolytic tank has proved notably successful. After eight months' use, in the third week of April, 30 gallons of sludge were withdrawn for analysis and on June 13, after ten months' operation, the tank was stirred up and emptied and a representative sample taken for analysis. The withdrawal of sludge and the examination of the tank were solely for the purpose of studying the process and were not conditioned by any obvious accumulation of sludge; and the weekly analyses showed no tendency to deterioration. In fact no accumulation of sludge was apparent by probing from the top of the tank.

From the average analyses of sewage and effluent, and from the analyses of sludge and tank contents, we have calculated the removal of suspended solids and organic nitrogen and the proportion of the deposited solids liquefied, in Table 10. The figures cover the whole period up to June 13 and therefore differ slightly from those given in Tables 7 and 8.

These figures show, as do those in Tables 7 and 8, a removal of about half the suspended solids in the crude sewage. The most important point however is brought out in the last line, which shows that 72 per cent of the total solids and 81 per cent of the volatile

TABLE 10.

EFFICIENCY OF BIOLYTIC TANK. AUGUST, 1909—JULY, 1910.

Parts per million.

	Suspended Solids			Suspended Organic Nitrogen
	Total	Volatile	Fixed	
Sewage	166	114	52	4.4
Tank effluent	77	50	27	2.4
Deposited in tank	89	64	25	2.0
Found in tank	25.2	12.6	12.6	.9
Per cent of total removed by tank	54	56	48	45
Per cent of deposited solids dissolved	72	81	49	52

solids deposited were eliminated by septic action. This result is a very favorable one, as indicated by Table 11, in which the figures for a number of English and American tanks are brought together for comparison (from Kinnicutt, Winslow, and Pratt, 1910).

TABLE 11.

LIQUEFYING EFFICIENCY OF SEPTIC TANKS.

Percentage of Deposited Solids Dissolved.

Place	Total Solids	Place	Total Solids	Organic Solids
Birmingham, England	10	London, England	41	71
Exeter, England*	25	Boston, Mass.†	42	81
Manchester, England	26	Glasgow, Scotland	50	..
Ilford, England	30	Hampton, England	..	58
Sheffield, England	30	Saratoga, N.Y.	69	..
Accrington, England	35	Boston, Mass.‡	72	81
Worcester, Mass	39	Exeter, England§	80	..
Leeds, England	20–60			
Huddersfield, England	40			

* Royal Commission studies.
† 1905–7. Rectangular tanks.
‡ 1909–10. Hydrolytic tank.
§ Early reports from town.

Except for the very high reduction originally reported from Exeter, the efficiency of the biolytic tank in the liquefaction of total suspended solids appears to be much greater than that of most septic tanks of the ordinary form. The tank at Saratoga is the only one which equals it, and this tank has the advantage of receiving its chief burden in summer when the temperature is favorable to active bacterial development. In regard to volatile suspended solids the old rectangular tanks used at the Technology Station in 1905–7 were equally efficient. These tanks, however, were in a shed and thus protected from winter weather, and their vigorous liquefaction of volatile suspended solids was counterbalanced by an actual increase in fixed suspended solids.

Altogether it seems that the use of a conical tank with upward flow for septic treatment is justified by our results. The removal of suspended solids is about as good as that attained with a rectangular tank and the liquefaction of the deposited solids is distinctly better.

The effluent from the biolytic tank, as noted above, passed to a dosing tank of 850 gallons capacity, which if discharged once in five hours gives a rate on the sand bed of 4,250 gallons per day or approximately 400,000 gallons per acre per day.

The actual net rates on account of slackening in the flow of the septic tank and Sunday rests were considerably lower, as shown by months in Table 12.

TABLE 12.

SAND FILTER RATINGS.

Rates in gallons per acre per day.

1909–10	No. Gallons
Up to January 1	293,000
January	342,000
February	337,000
March	315,000
April	221,000
May	245,000

The general operation of the bed at this high rate was notably successful. The dose of sewage disappeared ordinarily in fifteen minutes. This period gradually increased however in the colder weather until sewage stood on the bed from one dosing to the next. It was merely necessary to rake the bed to relieve the clogging.

During ten months of operation no material was removed from the bed and there was no apparent tendency to clogging or other sign of deterioration. The surface was raked six times, on November 6, January 24, January 31, February 28, March 7, and April 9. On November 22 the bed was furrowed for the winter and on March 17 it was leveled again. Ice formation was complete over the furrows for periods of three or four days in the coldest weather. The warmth of the sewage beneath together with that from the sun soon broke the ice directly above the channels. No doubt the frequent application of sewage tended to protect the bed from the more severe effects of winter weather.

The sand bed will undoubtedly clog in the future and it will be

necessary to scrape its surface and remove sludge deposit as is done in all plants under actual operation. The important point however is that with the application of septicized effluent the clogging is so gradual that the accumulation of solids from ten months of operation did not affect its efficiency in any appreciable degree. Such being the case, the removal of sludge deposit during the cold winter months could easily be avoided, without reducing the intensive rate of operation.

The composition of the filter effluent is indicated by the results tabulated in Table 13.

TABLE 13.

COMPOSITION OF EFFLUENT FROM THE INTERMITTENT FILTER.

Monthly Averages of Weekly Composite Sample. Parts per million.

Month 1909–10	Nitrogen as					Oxygen Consumed		Relative Stability
	Total	Organic	Free Ammonia	Nitrites	Nitrates	30′ Boiling	15′ Cold	
August	19	10.5	2.2	.2	6.2	12	2.0	96+
September	19	7.4	1.9	.1	9.5	16	1.9	96+
October	21	7.1	.4	.3	13.0	14	1.6	93
November	26	5.5	5.7	.4	14.0	17	2.4	96+
December	28	8.5	4.3	.3	15.3	16	2.5	95
January	26	5.2	5.7	.1	15.3	15	1.9	96+
February	22	5.1	4.2	.1	12.7	11	2.1	96+
March	28	3.3	4.0	.0	21.0	14	1.6	96+
April	48	4.0	1.5	.0	42.0	20	2.4	96+
May	45	2.3	1.1	.1	41.6	18	3.2	96+
Average	28	5.9	3.1	.2	19.1	15	2.2	96

The usual seasonable phenomena are indicated, free ammonia and organic nitrogen rising in November and December as the cold weather checks bacterial action. In March these organic constituents drop again, and the nitrates rise, reaching the enormous value of 40 parts and over in April and May. In these two months about 90 per cent of the total nitrogen discharged was in the nitric form.

A better idea of the work of the bed may be gained from Table 14, in which the effluent is compared with the applied liquor. In spite of the fact that the total nitrogen was 27 per cent more in the effluent than in the applied liquor (due perhaps in part to concentration by evaporation from the surface of the bed), the free ammonia showed a purification of 79 per cent, the oxygen consumed determined at 212° F. a purification of 72 per cent, and the more

unstable portion as determined in the cold a purification of 86 per cent. For the whole period 69 per cent of the nitrogen present in the effluent was in the mineral form.

TABLE 14.

EFFICIENCY OF INTERMITTENT FILTER.

Parts per million.

	Nitrogen as					Oxygen Consumed	
	Total	Organic	Free Ammonia	Nitrites	Nitrates	30' Boiling	15' Cold
Septic Effluents....	22	7.5	14.6	0.0	0.1	54	16.2
Sand effluents......	28	5.9	3.1	0.2	19.1	15	2.2
Percentage purification............	21	...	79	...	....	72	86

The effluent from the bed was always of excellent appearance and free from turbidity and odor. Its stability is given in the table as 96. This corresponds to the maximum period of 14 days for which the methylene blue samples were kept (Phelps, 1909). As a matter of fact the true stability must have been between 96 and 100, probably nearer 100. Out of 41 weekly averages for stability 35 were 96, or the maximum; one week averaged 95, two weeks 94 each, one 93, one 92, and one 88. The last of these values corresponds to a reducing time of between 9 and 10 days, so that it is evident that the effluent was uniformly of a very high quality.

These experiments are being continued and will be more fully reported after a longer period. After ten months of operation however the results seem to indicate clearly that intermittent sand filters can be operated at high rates (400,000 gallons per acre per day) with marked success, if the beds are carefully constructed of fairly coarse sand and dosed at regular and frequent intervals with sewage from which suspended solids have been partially removed by preliminary treatment. Our experience suggests that preliminary treatment can with advantage be carried out in a deep tank with upward flow, the removal of suspended solids by such a tank being fairly efficient and the liquefaction of the deposited solids unusually high.

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